LABORATORY STUDIES ON THE EXCITATION AND COLLISIONAL DEACTIVATION OF METASTABLE ATOMS AND MOLECULES IN THE AURORA AND DAY AIRGLOW

January 1966

A Progress Report on Research Supported by the National Aeronautics and Space Administration Under Grant NGR 39-011-030.

Prepared by

The University of Pittsburgh

Department of Physics

Space Research Coordination Center

Pittsburgh, Pa. 15213

for

The National Aeronautics and Space Administration

Edward C. Zipf
Principal Investigator

1. INTRODUCTION

The University of Pittsburgh with the support of the National Aeronautics and Space Administration (NGR 39-011-030) has initiated a theoretical and experimental program to study the excitation and collisional deactivation of metastable atoms and molecules in the upper atmosphere. In its initial phase this laboratory-oriented program is concentrating on two metastable species that are observed in auroras and the airglow: the ^1D state of atomic oxygen and the $A^3\Sigma_u^+$ state of molecular nitrogen.

The forbidden lines and bands emitted by $O(^1D)$ atoms and $N_2(A^3\Sigma_u^+)$ molecules in the upper atmosphere are prominent in the visible and near-ultraviolet spectrum of the aurora and airglow. Some information on the density and altitude distribution of these metastalbe species in the upper atmosphere has been obtained from satellite and rocket observations of these emission features. Although the field data are fragmentary, they do clearly show that the physical processes responsible for the creation and destruction of these metastable states in the aurora and airglow are more complex then previously imagined and that our present knowledge of the physical properties of the ^1D state of atomic oxygen and the $A^3\Sigma_u^+$ state of molecular nitrogen is insufficient to account for many of the field observations. The experimental program that is now under development at the University of Pittsburgh represents a systematic attempt to provide the necessary quantitative basis for interpreting existing rocket and satellite data and for suggesting future field experiments.

The experimental work described in this report was performed in laboratories located in the new Space Research Coordination Center of the

University of Pittsburgh, which was built with a grant from the National Aeronautics and Space Administration. This facility houses an interdisciplinary faculty, and the cross-fertilization possible in such an environment has already contributed in a number of significant ways to the metastable program.

This report discusses briefly the progress that has been made in implementing this program since May 1, 1965. In section 2 we review the current status of the auroral and day glow problem as it relates to the goals of the laboratory program. In section 3 we describe the versatile data processing system that will be used in these studies, and whose installation is nearly complete. In section 4 we discuss the progress we have made in the theoretical phase of the program. In particular we will describe the computer programs that have been developed to process our laboratory data and then we will discuss a paper that we delivered recently at the Gaseous Electronics Conference (Minneapolis, 1965) on electron-ion recombination and on the destruction of $N_2(A^3\Sigma_u^+)$ molecules in the afterglow. In section 5 we outline our laboratory plans for the next six months and we discuss the close relationship between the present laboratory work and a complex auroral-rocket experiment scheduled for launch during February, 1966 from Fort Churchill. The field experiment involves the joint efforts of the University of Pittsubrgh, the Johns Hopkins University, and the University of Colorado. Sections 6 and 7 lists the personnel participating in the laboratory work and the published papers contributed by this program.

2. REVIEW OF AURORAL AND AIRGLOW PROBLEM

2-1. <u>The λ6300 Dayglow</u>. A quantitative explanation of the excitation

and collisional deactivation of the ^1D state of atomic oxygen in the dayglow remains one of the most intriquing - and as yet unsolved - aeronomy problems. The ^1D state is the lowest excited state of atomic oxygen with an excitation energy of 1.96 ev. Radiative transitions from this state to the ground state are forbidden by a spin selection rule. The radiative lifetime of the ^1D state has not been measured; the calculated value for this lifetime is 110 seconds. Two forbidden lines (λ6300 and λ6364) originate from this state. Both have been observed in auroras and the airglow; the λ6300 line is about 3 times as bright as the companion λ6364 line.

The altitude distribution of λ6300 in the dayglow was measured on May 7, 1963 by Zipf and Fastie[1] when the sun was at a zenith distance or 60°. Noxon[2] has made extensive ground-bases studies of this line at two northern latitudes (Boston and Fort Churchill, Manitoba). The behavior of the red line in the dayglow can best be described as anomalous; its intensity is characterized by a striking variability while all other geophysical indicators (e.g., magnetic acitvity) remain essentially constant. The intensity of this line, for example, has been observed to increase by an order of magnitude in a few minutes from a few kilorayleigh to 50 kR, then remain enhanced for several hours and finally return rapidly to its original low value. At the present moment only Noxon's instrument at Harvard is making synoptic studies of the red line from the ground. It would be highly desirable to have similar instruments at other installations to provide additional data on the red line in the dayglow. This is a particularly important time at which to begin since we are still near the minimum of the solar

cycle and so have the opportunity to monitor the behavior of the red line as the solar activity increases.

The present theory of the excitation of the red line in the dayglow is based on the following mechanisms;

I. Excitation:

(i) Photodissociation of O_2 in the Schumann-Runge Continuum

$$O_2 + h\nu \rightarrow O(^1D) + O \qquad (1)$$

(ii) Electron-ion Recombination

$$O_2^+ + e \rightarrow O(^1D) + O \qquad (2)$$

$$NO^+ + e \rightarrow O(^1D) + N \qquad (3)$$

(iii) Electron Impact

$$O(^3P) + e \rightarrow O(^1D) + e \qquad (4)$$

II. Deactivation

$$O(^1D) + N_2 \rightarrow O(^3P) + N_2^* \qquad (5)$$

$$O(^1D) + O_2 \rightarrow O(^3P) + O_2^* \qquad (6)$$

The theoretical analysis of the λ6300 dayglow is hampered by the meagre amount of laboratory data on the various rate coefficients and cross sections for the processes listed above. For example, although the theoretical values for (I - 4) suggest that this process is indeed an extremely important source of the red line in the F region of the ionosphere, no measurements have been made of the cross section for electron excitation of the ^1D state. Similarly, only contradictory values (differing by several orders of magnitude in some cases) for the reaction rates for the collisional deactivation of $O(^1D)$ atoms by the atmospheric gases (II - 5,6) are available. The quantitative problem is further complicated by the large temperature range involved in

the airglow from 300°K to as much as 2000°K. As a result, not only must we measure these cross sections at room temperature, but we must also determine their temperature dependence over a very wide range. None of this has been done.

In defense of the experimentalists, however, we should hasten to point out that laboratory studies on the $O(^1D)$ state present formidable difficulties to be overcome - many of which are beyond the capabilities of the present state of the art. In spite of the complex problems involved, the λ6300 dayglow warrants an intense effort on the part of laboratory workers because it is one of the central problems in aeronomy today.

2-2. The Auroral Excitation of the Vegard-Kaplan System

The $A^3\Sigma_u^+$ state is the lowest excited electronic state of nitrogen. Radiative transitions from this state to the ground state of the N_2 molecule are forbidden by a spin selection rule. The $A^3\Sigma_u^+$ state appears to have a very long radiative lifetime - approximately 21 seconds. In spite of this, nitrogen molecules are excited to this state in sufficient abundance in auroras so that the forbidden Vegard-Kaplan system ($A^3\Sigma_u^+ \; x^1\Sigma_g^+$) is the dominant feature in the ultraviolet auroral spectrum extending from 2000A to 3000A.

Two excitation mechanisms have been proposed to account for the emission of the Vegard-Kaplan bands in an aurora:

(i) Electron bombardment

$$N_2(X^1\Sigma_g^+) + e \rightarrow N_2(A^3\Sigma_u^+) + e \qquad (7)$$

and (ii) Cascade Radiation

$$N_2(C^3\Pi_u) \rightarrow N_2(B^3\Pi_g) + h\nu \text{ (Second Positive System)} \quad (8)$$

$$N_2(B^3\Pi_g) \rightarrow N_2(A^3\Sigma_u^+) + h\nu \text{ (First Positive System)} \quad (9)$$

Electron bombardment tends to excite preferentially the higher vibrational levels of the $A^3\Sigma_u^+$ state ($v' > 4$) because this process is strongly dominated by the Franck - Condon factors for the $A^3\Sigma_u^+$ and $X'\Sigma_g^+$ states. Curiously, the very high vibrational levels favored by (7) are either not observed or they appear very weakly in auroras. This has led Hunten and Broadfoot[3] to conclude that electron bombardment is unimportant.

The observation, however, may be explained equally well by assuming that the upper vibrational levels of the $A^3\Sigma_u^+$ state are more rapidly depopulated by collisional procsses. This would allow process (7) to be as important in the upper atmosphere as the laboratory measurements of the electron-excitation cross sections would seem to require, and at the same time it would explain the absence of light emission from the higher vibrational levels. This explanation is also consistent with quantitative observations of a very small cross section for the collisional deactivation of $N_2(A^3\Sigma_u^+, v' = 0, 1)$ by ground state N_2 molecules by Noxon[4] and Zipf[5] ($\sigma \leq 3 \times 10^{-22}$ cm^2), in contrast with qualitative observations by the same workers of an apparently large cross section for the same process for $N_2(A^3\Sigma_u^+, v' > 1)$. Further laboratory work on this problem is needed.

A second unsolved problem involving the emission of the Vegard-Kaplan bands in an aurora is posed by the simple fact that few of the $N_2(A^3\Sigma_u^+)$ molecules formed in an aurora ever survive long enough to radiate. Both rocket and ground-based measurements show that at low altitudes (~110 km) $N_2(A^3\Sigma_u^+)$ molecules are rapidly destroyed in collisions with other atmospheric

gases. Laboratory studies by Zipf and Noxon clearly rule out ground-state N_2 molecules in the cases of $N_2(A^3\Sigma_u^+)$ molecules in the $v' = 0$ or 1 vibrational levels. The identity of the quenching species is not known. However, only O and O_2 exist in sufficient abundance at these altitudes to be likely candidates. This auroral problem is also amenable to study in the laboratory.

In addition to the above unsolved collisional-deactivation problems, $N_2(A^3\Sigma_u^+)$ molecules exhibit other behavioral anomalies in auroras that have yet to be explained. Perhaps the most interesting is the observation by Hunten and others, that the rotational temperature of the Vegard-Kaplan bands in an aurora is always about 850°K. Because of its very long radiative lifetime, it is generally assumed the molecules in the $A^3\Sigma_u^+$ will rapidly come into thermal equilibrium with the ambient gas. In this case the rotational temperature would be equal to the gas temperature. Using this argument Hunten[3] has interpreted the field observations as evidence that the Vegard-Kaplan bands are emitted from altitudes in excess of 220 km. The conclusion, however, is not compatible with our auroral rocket data, which clearly show intense V-K band emission at altitudes as low as 110-120 km, where the temperature is about 300°K. To further complicate matters when the Vegard-Kaplan bands are excited in laboratory discharges, their rotational temperature is usually equal to the ambient gas temperature. The difference in behavior apparently reflects in some way a peculiarity in the excitation and collisional deactivation of $N_2(A^3\Sigma_u^+)$ molecules in auroras that is not duplicated in these laboratory experiments. This anomalous behavior certainly bears further field and laboratory attention.

3. LABORATORY FACILITY FOR ATOMIC AND MOLECULAR COLLISION STUDIES.

3-1. A versatile data processing system that will permit time-dependent studies of atomic and molecular collision processes, is currently being installed in our laboratory. This pulse-counting system makes maximum effective use of the IBM 7090 computer operated by the University of Pittsburgh, and has a dynamic range in time and sensitivity that is limited only by the current state of the art. The system may be used, for example, to study collision processes occurring on a nanosecond time scale with a resolution of about 0.1 nanoseconds or to study the time-dependent behavior of oxygen atoms in the ^1D state in the afterglow by measuring the extremely feeble radiation emitted by these atoms even though their radiative lifetime is 110 seconds. This is accomplished by a signal averaging technique that will be discussed in more detail later.

The laboratory facility is arranged physically so that a number of distinct and possible unrelated experiments can be set up in adjoining laboratory rooms. These experiments will be linked by cable to the central data processing unit and will use this facility on a shared-time basis. Because of the great speed with which the data can be collected and transferred to computer compatible tapes, a large number of experiments may be accommodated virtually simultaneously. In addition, because timing, calibration, and other programming signals can originate from the central system, it will be unnecessary to duplicate many common, electronic components at each experimental site, thereby substantially reducing the cost of individual experiments and simplifing the maintainance problem. In planning this laboratory we have made a conscious effort to

adopt the central-facility philosophy and computer technology so successful used in nuclear physics.

3-2. In this section we will describe briefly the signal averaging technique that we have developed for making highly precise measurements of the time-dependent behavior of metastable $N_2(A^3\Sigma_u^+)$ molecules in the afterglow. The metastable N_2 molecules are produced in a pulsed microwave discharge in highly purified nitrogen. The discharge takes place in a small cylindrical quartz cell located at the center of a microwave cavity resonant in the TM_{010} mode at 2900 Mc/sec. The metastable molecules are detected and studied as a function of time and pressure in the afterglow by measuring the intensity of selected Vegard-Kaplan bands. A Ebert-Fastie monochromator is used to select individual V-K bands for study.

Figure 1 shows a block diagram of this apparatus. The core of the data processing system is a 512 channel analyzer that has both pulse-height and multi-scaling capabilities. Each channel can store 10^6 counts. Data stored in the memory of this device may be readout in several modes. For immediate (though less precise) analysis the data may be displayed on an oscilloscope or plotted by an X-Y recorder. For a more detailed quantitative analysis the contents of the memory can be printed out by an IBM typewriter or punched onto an IBM computer-compatible tape. In an experiment where signal averaging is used, the analyzer is programmed externally in the multiscaling mode.

A schematic diagram of the timing and logic signals used to program such an experiment are shown in figure 2. In the particular experiment illustrated, the microwave discharge that creates the metastable N_2 molecules, is excited for a period of 100 μsec every 10 msec (repition rate

of 100 cps). The microwave power pulse that is used for this purpose, is generated by a QK-60 magnetron which is turned on by the power-pulse gate shown in the diagram. The time period between the termination of the power pulse and the leading edge of the succeeding power pulse (900 μsec in this example) is called the afterglow period. During this interval $N_2(A^3\Sigma_u^+)$ molecules created during the discharge are destroyed by the mechanisms discussed in section 4.

These collisional loss processes are studied by observing the photons emitted by the excited $N_2(A^3\Sigma_u^+)$ molecules by making time-dependent absolute measurements of the intensity of this radiation in the afterglow. This is accomplished by using a time - sampling technique: The afterglow period is divided into a number of time intervals with a window width, Δt. These time or data intervals are determined by the data gates shown in figure 2. Photons detected by the photomultiplier tube during one of these intervals are counted, and the counts are stored in one channel of the 512-channel analyzer. When the data gate closes an ACS pulse is generated which steps the analyzer to the next channel, which is then ready to store the photon counts that occur during the time interval controlled by very next data gate. In this manner the analyzer is stepped through a number of channels during the afterglow period collecting data during these predetermined time intervals.

In any one cycle only a few counts may be received in a given channel, so that the statistics for a single cycle will be poor. To overcome this problem the system is cycled with the timing signals phased so that photons arriving at the same time with respect to the power pulse are stored in the same channel. This is achieved with the help of the RCS gate which auto-

matically resets the channel scalar to channel one shortly before the arrival of the next power pulse. Hence the analyzer is always in channel one during the time the discharge is being produced. The inhibit gate controls the linear gate (figure 1), and prevents photoncounts from being recorded during the discharge period. We note in passing that the individual photoelectron pulses that are generated by the incident photons are first amplified and then sampled by a single - channel pulse height analyzer which accepts only those photoelectron pulses with specified amplitude characteristics and then generates a standard output pulse. The standardized pulse is then fed to the linear gate controlled by the inhibit signal.

Additional circuitry has also been developed which makes sure that the analyzer can be turned on and off only after the RCS signal has returned the channel scalar to the first channel. This is necessary so that all data channels will have had an equal opportunity to collect counts.

The method outlined here for making time-dependent measurements of afterglow radiation has three striking advantages over previously used techniques. (1) Because it is a counting measurement, widely used statistical techniques can be used to determine the inherent accuracy of the data points. (2) These statistical criteria can also be used to optimize the collection of data. This is a signal averaging technique and with each succeeding cycle the statistics improve. The system can therefore be allowed to cycle until the last desired data point has the required statistical accuracy (e.g. 3% statistics requires about 10^3 counts). (3) Finally, a very substantial reduction in the total time needed to accumulate the necessary data is achieved by actually collecting counts at many

points in the afterglow period. Based on previous experience with $N_2(A^3\Sigma_u^+)$ studies using older techniques, measurements that previously required 4-5 hours to complete, will now take about 15 minutes. This improvement involves more than just the time compression. It, for example, means that the system need be exceptionally stable for only a few minutes instead of several hours. The problem of maintaining the high purity of the gases that we use is also simplified. But perhaps most important, the increased data-collecting speed will allow us to determine more quickly what are the best avenues along which to proceed in a given experiment.

4. THEORETICAL CALCULATIONS AND DATA ANALYSIS

4-1. In order to fully exploit the potentialities of the data processing system described in section 3, we have developed a number of computer programs to solve non-linear partial differential equations by an implicit method. These programs will be used in two important problem areas:

(a) to analyze experimental data (e.g., light intensity measurements made in afterglow experiments) to obtain values for such quantities as diffusion coefficients, reaction rates, radiative lifetimes, and recombination coefficients by fitting a numerical solution of the appropriate conservation equation to these data by means of a least squares procedure. This method permits data reduction and analysis without resorting to oversimplified models, and in addition, facilitates the rapid treatment of large volumes of data by a digital computer. These programes were formulated and tested during the period covered by this report. The acquisition of this capability was an important step

in the development of our automatic data processing system.

(b) to evaluate the magnitude of the experimental errors introduced into the measurement of reaction rates and recombination coefficients because of the averaging techniques used in most of these experiments.

4-2. Numerical analyses of the type described in section (4-1) were recently applied to laboratory data on the destruction of nitrogen molecules in the metastable $A^3\Sigma_u^+$ state in the afterglow and to assess the magnitude of the errors introduced into the measurement of the volume recombination coefficient (2 body electron - ion recombination) by second order non-linear loss processes. In this section we summarize the findings of these studies which we reported recently at the 18th annual Gaseous Electronics Conference.

We have considered two problems that are governed by a non-linear continuity equation having the same general form,

$$\frac{\partial n}{\partial t} = D\nabla^2 n - \alpha n^2 \qquad (10)$$

but which have volume emission rates in the afterglow that depend in a different way on the density of the active species.

The first class of problems involve metastable atoms or molecules that are destroyed by diffusion to the walls of the discharge cell, and by metastable-metastable collisions. The volume emission rate, ϵ, in this case is directly proportional to the metastable density ($\epsilon = An$) and may vary in a complex way with both time and position in the gas volume. The intensity or the surface brightness of the afterglow, which is what experimentalists generally measure, involves the integral of the

local volume emission rate over a limited portion of the gas volume

$$I(t) = \int \varepsilon(\vec{r},t)\, d\vec{r} = A \int n(\vec{r},t)\, d\vec{r} \qquad (11)$$

The domain of the integration depends in part on the particular optical system used in the experiment. It is important to note that the observed intensity may vary because of two independent effects: the first, due to the actual loss of active particles because of the basic atomic loss processes themselves, and the second, due to a spatial redistribution of the active particles within the integration domain itself. At various times within the afterglow period these effects may counterbalance each other, producing an artificially slow intensity decay, or perhaps re-enforce one another thereby increasing the apparent rate with which the afterglow radiation decays. If one does not simultaneously measure the spatial distribution of the excited atoms, these effects may introduce errors into the numerical values of such quantities as the recombination coefficient, reaction rate, radiative lifetimes and other similar quantities that are inferred from absolute surface brightness measurements in the afterglow.

The second class of problems involves the allowed radiation produced in a 2-body electron-ion recombination process. Here the volume emission rate varies as the square of the local electron density [$\varepsilon = \alpha n(e)^2$] provided there is only one species of positive ions and no negative ions. The surface brightness now involves a spatial integral over the square of the electron density,

$$I(t) = \alpha \int n_e(\vec{r},t)^2 d\vec{r} \qquad (12)$$

and has a different time history than its metastable counterpart [equation (11)]. The conventional theory used by most workers in analyzing electron-ion recombination data assumes that the intensity of the recombination radiation varies directly with the square of the electron density in the afterglow, that is $I(t) = kn_e(t)^2$. The validity of this assumption depends on the method used to measure the average electron density. In many afterglow experiments the average electron density is measured by means of a microwave probing technique. This involves a spatial average of the electron density weighted by the square of the probing electric field,

$$< n_e > = \frac{\int n(\vec{r},t)\ E^2(\vec{r})d\vec{r}}{\int E^2(\vec{r})d\vec{r}} \qquad (13)$$

Because the surface brightness measurement and the electron density measurement employ different averaging methods, these measurements are affected differently by changes in the spatial distribution of the local electron concentration. Consequently, one should not be surprised to find that under some conditions the average emission rate does not vary with the square of the average electron density as the simple theory requires.

We have attempted to study both the metastable and electron-ion recombination problems by solving numerically the non-linear continuity equation (10) which determines the time-dependent behavior of the electron

and metastable concentrations in the afterglow. From these solutions the volume emission rates, the surface brightness and the average electron density were computed and compared. In obtaining these solutions we have followed a scheme first developed by Gray and Kerr[6]. This consists of replacing the continuity equation (10) with a normalized equivalent by introducing the following variables

$$\rho = r/\Lambda$$

$$N = n/n_o$$

$$\beta = \frac{\alpha n_o \Lambda^2}{D}$$

$$\tau = \frac{Dt}{\Lambda^2}$$

where Λ is the fundamental diffusion length of the discharge cell, n_o is the electron or metastable density when r = o, t = o and D is the metastable or ambipolar diffusion coefficient. With these substitutions the continuity equation becomes

$$\frac{\partial N}{\partial \tau} = \frac{1}{\rho} \frac{\partial}{\partial \rho} \left(\rho \frac{\partial B}{\partial \rho}\right) - \beta N^2 \qquad (14)$$

for a simplified geometry (infinite cylinder). The solutions of the normalized continuity equation (14) are uniquely given when the initial spatial distribution of the active species is specified along with the value of the dimensionless parameter β. The parameter β has a simple physical significance: β is the ratio of the initial axial (or central) electron loss rate or metastable loss rate which would prevail in the

absence of diffusion, to the corresponding loss rate resulting from only diffusion in the fundamental mode.

Figure 3 shows some of the solutions that we have obtained with $\beta = 100$. The plot shows how the plasma (or metastable molecules), which initially had the spatial distribution of the fundamental diffusion mode, bulges outward toward the wall and then subsequently contracts. When $\tau = 0.0925$ units the plasma has reached its maximum outward extent; the plasma now begins to contract and a very late times in the afterglow finally returns to the distribution of the fundamental mode. In the case of $N_2(A^3\Sigma_u^+)$ metastables, this point is not reached at 10 torr until some 60-70 msec after the termination of the discharge.

As a specific example, we have used this theoretical model to analyze afterglow radiation emitted by metastable nitrogen molecules in the $A^3\Sigma_u^+$ state. In the afterglow $N_2(A^3\Sigma_u^+)$ molecules are destroyed principally by diffusion to the walls of the discharge cell and by metastable-metastable collisions. Figure 4 shows how well the numerical solutions to equation (14) fit the experimental data both as a function of pressure, time, and the fundamental diffusion length of the discharge cell. We wish to point out that many important aspects of the decay of these auroral metastable molecules in the afterglow that were not previously amenable to detailed quantitative treatment are completely accounted for by this machine calculation.

The second specific problem that we are studying with the help of this computer program concerns the validity of laboratory measurements of the volume recombination coefficient for dissociative recombination:

$$X_2^+ + e \rightarrow X^* + X \qquad (15)$$

This electron-ion loss process is of great importance in the upper atmosphere. As we have noted above, this process is frequently studied in the laboratory by observing the radiation emitted by the excited atom X^*. Ideally the intensity of this radiation is directly proportional to the square of the electron density. This relationship is bases on simplifying assumptions about the method used to measure the intensity of this radiation. We have calculated the actual relationship between the measured values of the intensity and the average electron density by solving equation (14) numerically and using these solutions in equations (12) and (13). Figure 5 shows some of these results. We have plotted the slope of a log-log plot of the intensity versus the average electron density. The anticipated theoretical slope of 2 is indicated by the dotted line. In this illustration the plasma had an initial uniform distribution and the ratio of the radius of the discharge cell to that of the surrounding cavity was 0.5. As the curves show, the measured intensity varies more slowly with the average electron density than expected. It is only very late in the afterglow that the slope approaches the theoretical value of 2.0.

The calculations discussed very briefly in this section will be described in more detail in separate reports.

5. AN AURORAL ROCKET EXPERIMENT AND SIX-MONTH WORK PLAN FOR THE LABORATORY PROGRAM

5-1. The University of Pittsburgh in conjunction with the Johns

Hopkins University, and the University of Colorado have planned a complex auroral rocket experiment scheduled for launch on Feb. 15, 1966 from Fort Churchill, Manitoba. This field experiment has a direct bearing on the laboratory effort: it will study the excitation and collisional deactivation of the major band systems of nitrogen as well as several allowed and forbidden transitions of O1 in an aurora. The following processes will be studied in some detail:

(1) Electron-impact Excitation

$$N_2(X^1\Sigma_g^+) + e \rightarrow N_2(C^3\Pi_u) + e \quad (1)$$

$$N_2(X^1\Sigma_g^+) + e \rightarrow N_2(B^3\Pi_g) + e \quad (2)$$

$$N_2(X^1\Sigma_y^+) + e \rightarrow N_2(A^3\Sigma_u^+) + e \quad (3)$$

(ii) Cascade Radiation

$$N_2(C^3\Pi_u) \rightarrow N_2(B^3\Pi_g) + h\nu \text{ (Second Positive System)} \quad (4)$$

$$N_2(B^3\Pi_g) \rightarrow N_2(A^3\Sigma_u^+) + h\nu \text{ (First Positive System)} \quad (5)$$

$$N_2(A^3\Sigma_u^+) \rightarrow N_2(X^1\Sigma_g^+) + h\nu \text{ (Vigard-Kaplan System)} \quad (6)$$

(iii) Collisional Deactiviation Processes

$$O(^1D) + X \rightarrow O(^3P) + X^* \quad (7)$$

$$O(\ S) + X \rightarrow O(\ P) + X^* \quad (8)$$

$$N_2(A^3\Sigma_u^+) + X \rightarrow N_2(X^1\Sigma_g^+) + X^* \quad (9)$$

All of these processes and mechanisms are of immediate interest in our laboratory program. If the field experiment succeeds, we will be able to focus our attention in the laboratory more clearly on the key aspects of the auroral problem.

5-2. Work Plan. During the coming six months we will be concerned chiefly with completing work on the basic instrumentation that we will use in this program. This will include the design and testing of the various subsystems as well as actual prototype experimental measurements. Our work plan includes completing each of the following systems during this period with the exception of item #5 which represents a continuing need of our program:

1. Electronics for the data processing system. Work must be completed on the transistorized, master logic unit which programs the various subsystems and generates a variety of sequencing and command signals. At the present moment this job is about 80% finished.

2. Microwave Electronics. The circuits for the magnetron power supply and pulsed modulator have been designed and tested in their prototype form. Construction and testing of the final unit are scheduled for this work period.

3. Ultra-high Vacuum System. This system is about 50% completed. All of the required components are now on hand and we should be at the testing stage within one month.

4. Optical System. For the λ6300 experiment the optical system presents some unusual challenges. The solution to these problems depends to some extent on the outcome of a discussion (and negotiation) that is underway with Thin Films Products, Inc. of Cambridge, Mass. for the fabrication of highly specialized interference filters. Most of the other components for the optical system - including a refrigerated photomultiplier housing - are on hand. We have scheduled preliminary testing and absolute calibration of this system for late February.

5. Computer Analysis. The projects planned in this category fall into two areas. The first is devoted to refinements in our existing programs. Some of these programs need to be reformulated so that they use our IBM 7090 more economically. We also want to expand the capabilities of these programs, so that they may be used for a larger variety of problems. The second important area is to continue with our analysis of existing laboratory data on the $A^3\Sigma_u^+$ state of nitrogen.

6. PERSONNEL

The program discussed in this report is primarily a research program. Nevertheless, from the point of view of the University of Pittsburgh the opportunity that it opens to train space-oriented research workers, is very important. We are pleased to report that two students have joined this program: Mr. Michael Mumma who has successfully passed the Ph.D. comprehensive examination and is ready to begin work on his Ph.D. problem and Mr. Truman Parkinson, who has successfully passed the M.S. comprehensive examination and will take the Ph.D. comprehensive examination this spring (1966).

We also wish to report that at the 18th annual Gaseous Electronics Conference (Minneopolis, 1965), E. Zipf was elected to the executive committee of the Gaseous Electronics Conference.

7. PUBLISHED CONTRIBUTIONS AND REPORTS

(1) Bulletin of the American Physical Society, to be published, 1965.

ON THE MEASUREMENT OF RECOMBINATION RADIATION IN THE AFTERGLOW*. E. C. Zipf, University of Pittsburgh.

The intensity of the allowed radiation emitted by atoms excited in a 2-body electron-ion recombination process varies as the square of the electron density in a plasma with only one species of positive ions and no negative ions. This relationship has been used experimentally as a test for recombination radiation, and to evaluate the volume recombination coefficient α from afterglow data. In these studies the average emission rate per unit volume is usually inferred from a surface brightness measurement, while the average electron density is obtained by microwave methods. Because these measurements are affected differently by changes in the spatial distribution of the charged particles and excited atoms as the plasma decays, neither the measured intensity nor the average emission rate need vary as the square of the average electron density. To assess the magnitude of this effect, a numerical solution was obtained to the conservation equation with a quadratic loss term. From these results the average electron density, the intensity, and the average emission rate per unit volume of the recombination radiation were calculated and compared. It is found that the intensity of the recombination radiation may be related to the averate electron density by an expression
of the form: $$I(t) = k\,[n_e(t)]^2 + \varepsilon(t)$$
The magnitude of the time-dependent function $\varepsilon(t)$ and the conditions under which it approaches zero will be discussed.

* This work was supported by the National Aeronautics and Space Administration under Grant NGR 39-011-030

8. REFERENCES

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9. FIGURE CAPTIONS.

Figure 1. Block diagram of an afterglow experiment using signal averaging techniques.

Figure 2. Schematic diagram showing the logic and timing signals used to program a signal averaging experiment.

Figure 3. Time development of the electron (or metastable) density, assuming an initial diffusion distribution. $\beta = 100$.

Figure 4. A plot of the concentration of the metastable $N_2(A^3\Sigma_u^+)$ molecule versus time in the afterglow. The circles represent actual data points for several pressures and for two different fundamental diffusion lengths. The solid curves were obtained from a numerical solution of the non-linear continuity equation with the indicated β values.

Figure 5. A plot showing the relationship between the slope of a log-log plot of the afterglow intensity from 2-body electron-ion recombination versus the average electron density for an initial uniform distribution. The expected theoretical slope of 2.0 is indicated by the dashed line.

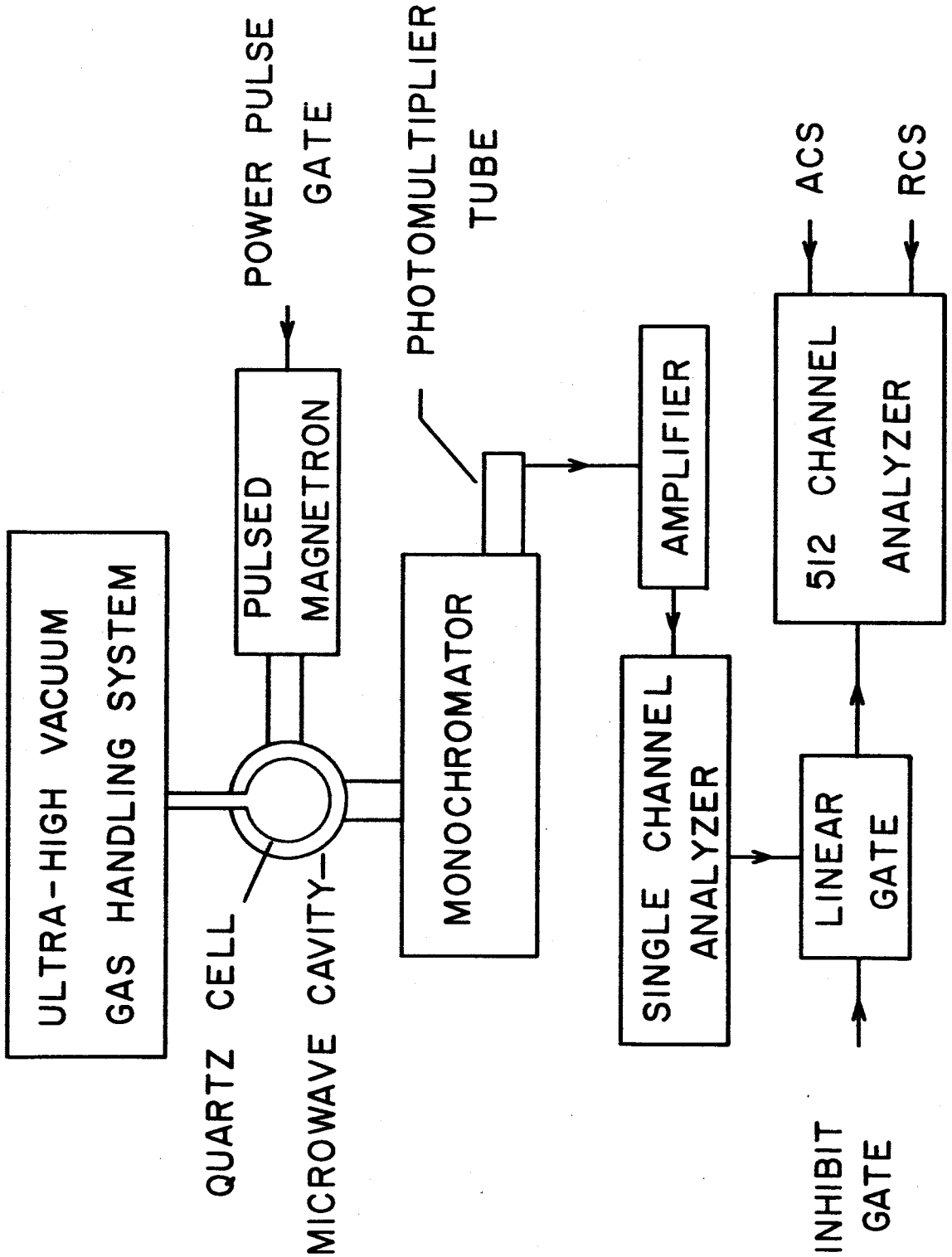
ULTRA-HIGH VACUUM
GAS HANDLING SYSTEM
QUARTZ CELL
MICROWAVE CAVITY
PULSED
MAGNETRON
POWER PULSE
GATE
PHOTOMULTIPLIER
TUBE
MONOCHROMATOR
AMPLIFIER
SINGLE CHANNEL
ANALYZER
LINEAR
GATE
INHIBIT
GATE
512 CHANNEL
ANALYZER
ACS
RCS

Figure 1

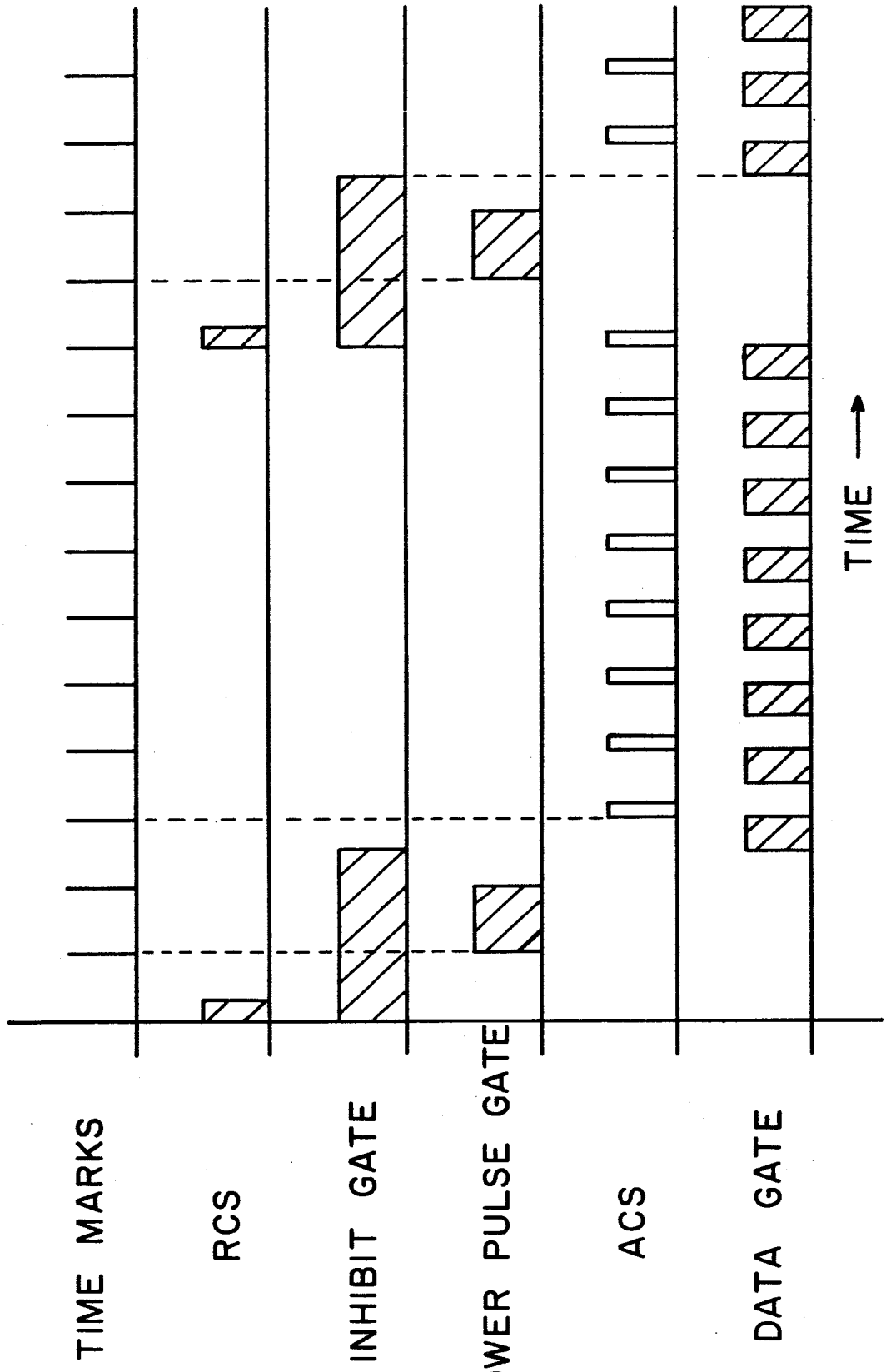
TIME MARKS
RCS
INHIBIT GATE
POWER PULSE GATE
ACS
DATA GATE
TIME
LOGIC GATES FOR SIGNAL AVERAGING EXPERIMENT

Figure 2

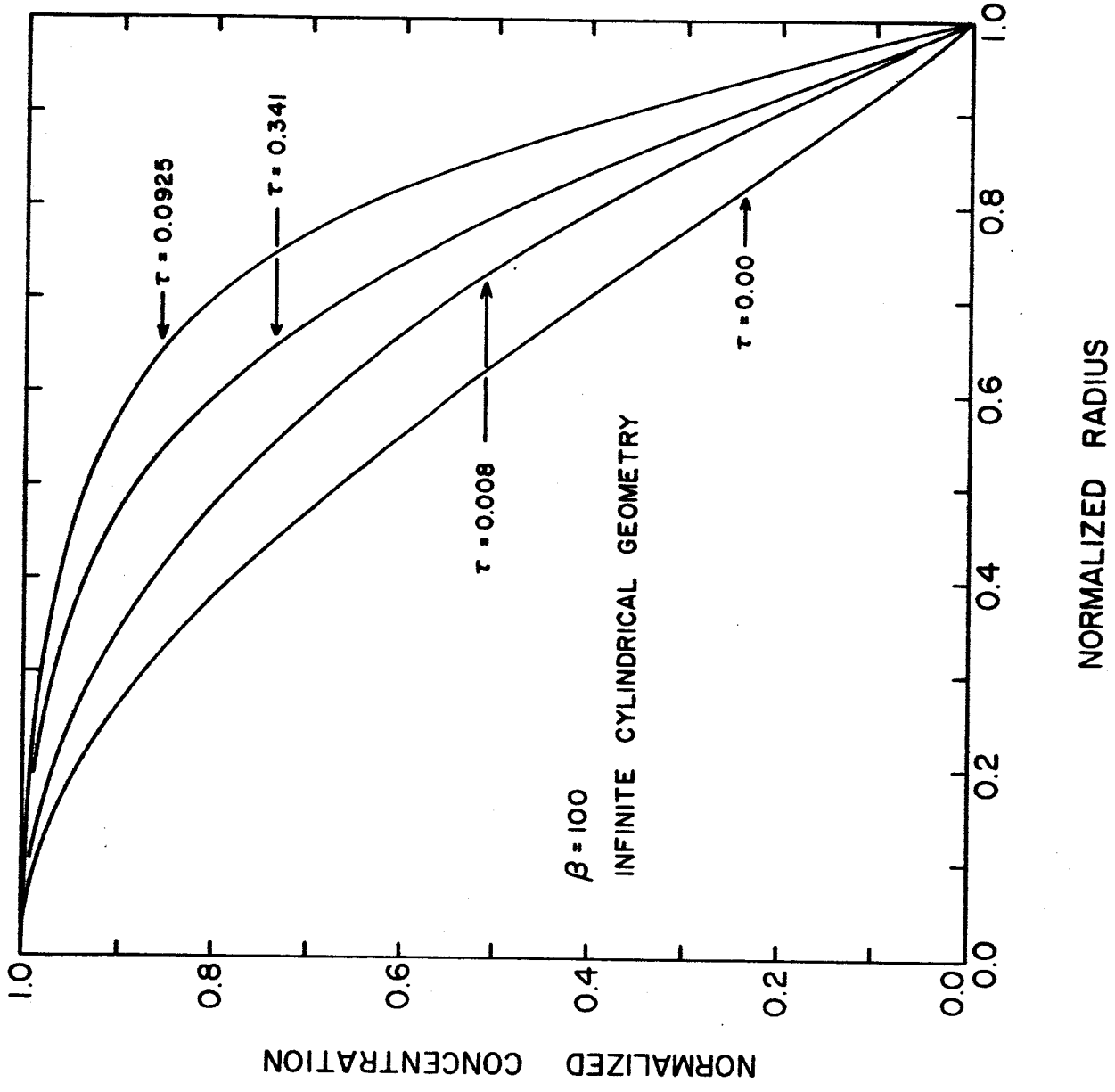
τ = 0.0925
τ = 0.341
τ = 0.008
τ = 0.00
β = 100
INFINITE CYLINDRICAL GEOMETRY
NORMALIZED CONCENTRATION
NORMALIZED RADIUS
0.0
0.2
0.4
0.6
0.8
1.0

Figure 3

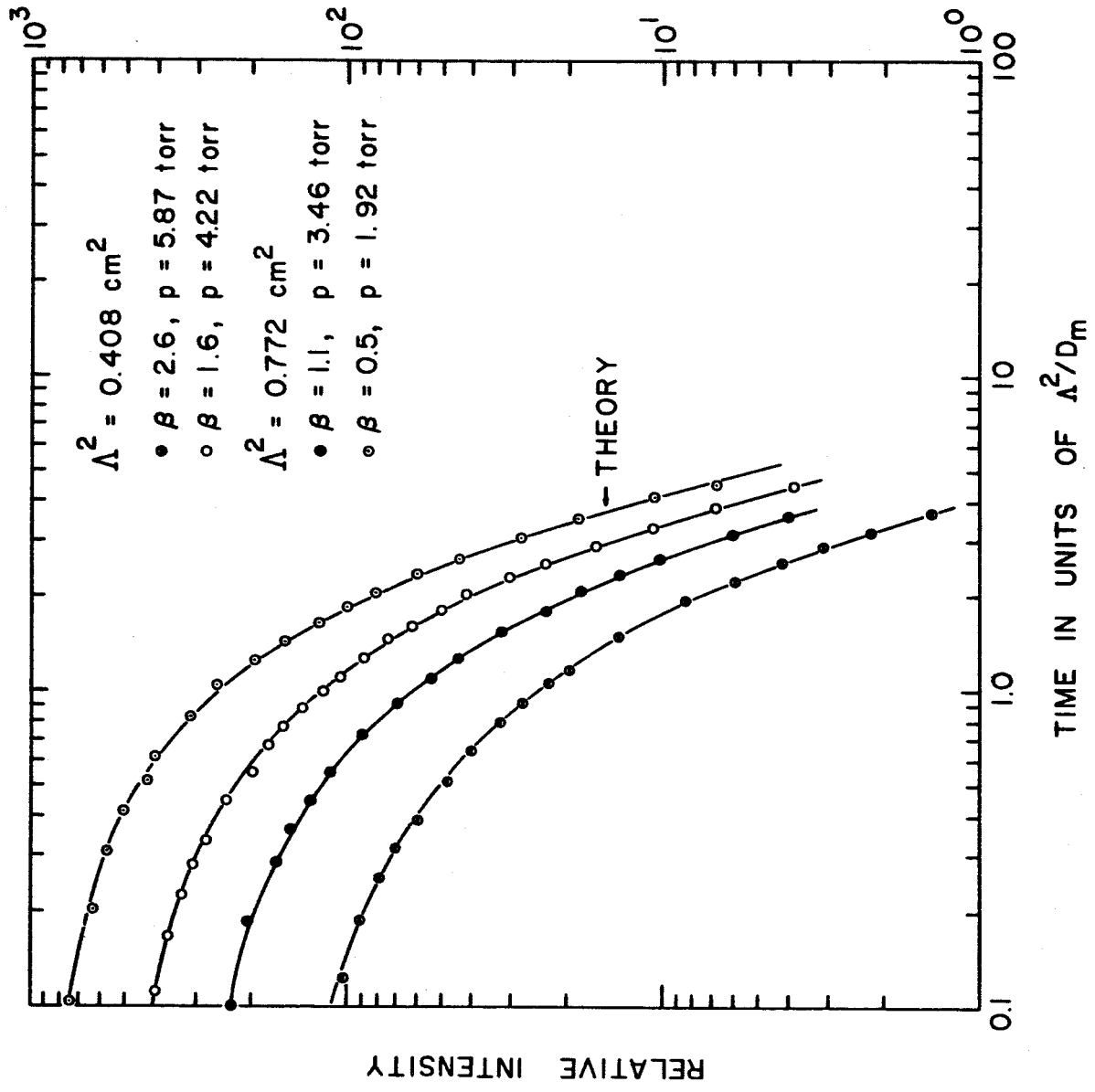
Λ^2 = 0.408 cm^2
● β = 2.6, p = 5.87 torr
○ β = 1.6, p = 4.22 torr
Λ^2 = 0.772 cm^2
● β = 1.1, p = 3.46 torr
○ β = 0.5, p = 1.92 torr
THEORY
RELATIVE INTENSITY
TIME IN UNITS OF Λ^2/D_m
10^3
10^2
10^1
10^0
100
10
1.0
0.1

Figure 4

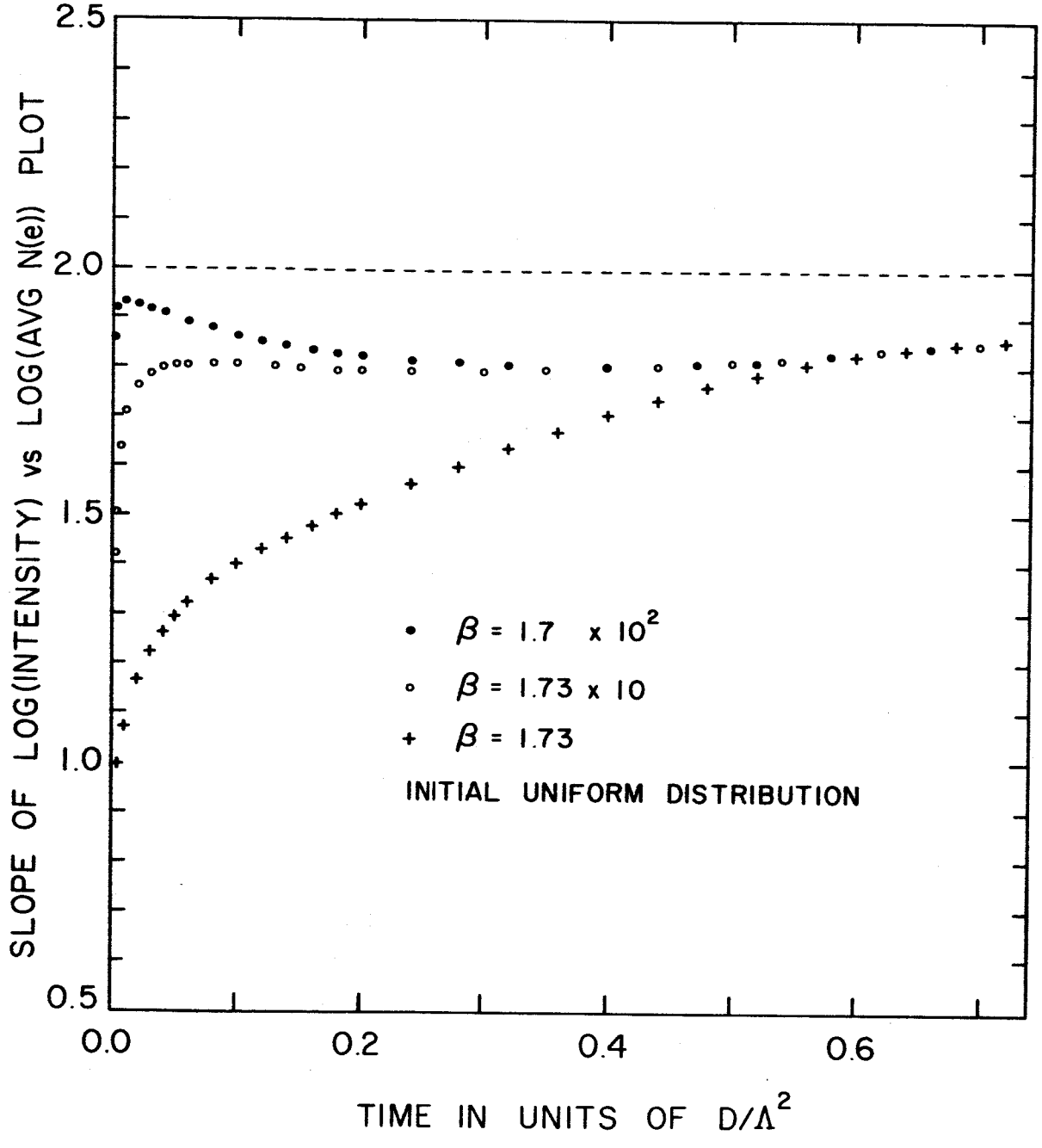
2.5
2.0
1.5
1.0
0.5
0.0
0.2
0.4
0.6
SLOPE OF LOG(INTENSITY) vs LOG(AVG N(e)) PLOT
TIME IN UNITS OF D/Λ²
β = 1.7 x 10²
β = 1.73 x 10
β = 1.73
INITIAL UNIFORM DISTRIBUTION

Figure 5